A New Upper Limit for the Tau-Neutrino Magnetic Moment

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Abstract

Using a prompt neutrino beam in which a ν_τ component was identified for the first time, the ν_τ magnetic moment was measured based on a search for an anomalous increase in the number of neutrino-electron interactions. One such event was observed when 2.3 were expected from background processes, giving an upper 90% confidence limit on μ_{ν_τ} of $3.9 \times 10^{-7}\mu_B$.

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I. INTRODUCTION

Magnetic moment measurements are an important tool for probing the fundamental structure of matter. Currently, precision measurements of the electron and muon magnetic moments are being used to probe the structure of the vacuum to the highest precision. A non-zero magnetic moment for any neutrino would be a clear and unambiguous signal for physics beyond the standard model. We have used the data collected for the Fermilab experiment E872 (DONUT) to perform a search for anomalous electromagnetic interactions of the tau-neutrino that would be a signature for a magnetic moment. This paper presents the first measurement of the ν_τ magnetic moment using a neutrino beam in which the ν_τ's have been positively identified.

The direct limits on ν_e and ν_μ magnetic moments are $\mu_{\nu_e} < 1.8 \times 10^{-10}\mu_B$ [1] and $\mu_{\nu_\mu} < 7.4 \times 10^{-10}\mu_B$ [2] and efforts are currently being made to extend these limits by another order of magnitude [3,4]. Because no direct measurements of the ν_τ component of a neutrino beam has been made until now, there has been no comparable measurement of its magnetic moment. In the CERN experiment WA66 [5], a limit of $\mu_{\nu_\tau} < 5.4 \times 10^{-7}\mu_B$ was based on an assumed flux of ν_τ's in the neutrino beam [6]. Elsewhere, indirect limits were derived from the duration of the supernova explosion SN1987A, giving a limit of $10^{-11}\mu_B$ for all neutrino flavors under the assumption that all neutrino flavors are equally produced in the supernova explosion.

More recently it has been argued [7] that the oscillation of atmospheric ν_μ to ν_τ would yield a limit of $\mu_{\nu_\tau} < 1.3 \times 10^{-7}\mu_B$. However, it has been pointed out that this value should be interpreted as a limit on the initial state ν_μ instead [8].

It used to be conventional to associate the properties of the neutrinos with their weak eigenstates ν_e, ν_μ, and ν_τ. The discovery of neutrino oscillations [9,10] implies that the electromagnetic properties of neutrinos should be associated with their mass eigenstates as opposed to their weak eigenstates [8]. Since the parameters of the mixing matrix are as yet undetermined, and there remains the possibility that neutrino mixing is further complicated by an additional sterile neutrino [11], the composition of any neutrino beam in terms of the mass eigenstates can at this stage not be determined. Until the oscillation scenario is fully understood, the electromagnetic properties should therefore be characterized by the initial neutrino flavor. This description is independent of any oscillation assumptions and allows for an extraction of the mass eigenstate magnetic moments when all of the mixing parameters are known [8].

In our measurement of the tau-neutrino magnetic moment we searched for an anomalous increase in the elastic neutrino-electron cross-section above the value predicted by the Standard Model. In the Standard Model neutrinos interact with electrons through Z^0 exchange, and a magnetic moment μ_ν adds an extra component due to photon exchange. The cross-section for a neutrino interacting via its magnetic moment with an electron is given in the high-energy limit by

$$\frac{d\sigma_\mu}{dT_e} = \frac{\mu_\nu^2}{\mu_B^2}\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right), \tag{1.1}$$

where T_e is the energy of the scattered electron in the laboratory frame [12]. The total magnetic moment scattering cross section is obtained by integrating over T_e. The lower

integration limit is given by the experimental threshold for low-energy electrons (0.1 GeV in this analysis). Since the neutrino undergoes a spin-flip when a photon is exchanged, there is no interference with the Standard Model process, and the total neutrino-electron scattering cross-section is just given by the sum of the two contributions.

Kinematic constraints [13] limit the angle between the incoming neutrino and the scattered electron in the laboratory frame to be

$$\theta^2_{\nu-e} < 2m_e/E_e \tag{1.2}$$

and for electron energies in excess of about 1 GeV, $\theta_{\nu-e}$ is less than 30 mrad. This angular constraint can be used as a clear signal to select neutrino-electron scattering events from the background of ν_e-nucleon charged-current events in which the electron is produced at a much larger angle.

II. THE APPARATUS

The Fermilab experiment E872 (DONUT) took data in 1997 and ν_τ-N charged current interactions were observed in nuclear emulsion [14]. Having established the existence of ν_τ in the ν beam and measuring the ratio of ν_e, ν_μ and ν_τ using charged current interactions, we searched for single electrons arising from ν interactions, the signature of a ν magnetic moment. The apparatus is described in detail elsewhere [15]; only the components central to this analysis will be discussed here.

The experiment consisted of three essential parts: a ν_τ enriched neutrino beam produced in a beam-dump target, a neutrino target, and a spectrometer with electron and muon identification. A "prompt" neutrino beam was produced by a beam of 800 GeV protons incident on a tungsten target. The target length and material were chosen so that most of the long-lived secondary particles would interact in the target before decaying, while the short-lived particles would decay before interacting. Hence the main contribution to the high-energy neutrino flux came from the decay of the short-lived D-mesons, with ν_e's and ν_μ's being produced in their semi-leptonic decays, and the ν_τ's primarily from the decay channel $D_s \rightarrow \tau\overline{\nu}_\tau$, $\tau \rightarrow \nu_\tau + X$. Downstream of the tungsten target there was 30 m of absorber material and two sweeping magnets to remove all but the neutrinos from the beam. ¿From our flux calculations using the LEPTO [16] particle generator and a GEANT [17] simulation, we estimate that in the sample of located events,the neutrino interactions would be 47% ν_μ charged current events, 27% ν_e charged current events, 5% ν_τ charged current events, and 21% neutral current events. This composition was confirmed by our measurements of charged current interactions [14].

Behind the absorber was the neutrino target region, shown in figure 1, consisting of four steel and emulsion modules that were interleaved with planes of 0.5 mm diameter scintillating fibers. The entire region was surrounded by lead shielding, 20 mm thick upstream and 6 mm thick downstream. The total target mass, including the upstream lead, was 554 kg. In front of the lead shielding was a wall of scintillator counters used in the trigger to veto interactions upstream of the target region.

The spectrometer consisted of the scintillating fiber tracker in the target region, drift chambers upstream and downstream of a wide-aperture analysis magnet, and a lead glass

array with a muon identification system behind it. The data acquisition system was triggered by a coincidence between a plane of scintillator counters just downstream of the target region and at least one of two planes of scintillators inside the region, together with no signal in the upstream veto wall.

In the search for anomalous ν-e interactions, the steel and emulsion target modules interleaved with the fiber tracker served as a high-granularity sampling calorimeter that allowed the identification and location of electromagnetic showers.

III. EVENT SELECTION

In the six-month run of the experiment 4.0×10^6 events were recorded for analysis and 2.0×10^5 of these had two or more tracks in the target region. Candidate neutrino-electron scattering events were selected from these events if the following requirements were met: there were no identified muons associated with the event; there was a signal in the trigger hodoscope directly downstream of the reconstructed vertex; the reconstructed tracks had an angle of less than 100 mrad with respect to the neutrino direction, and the reconstructed vertex was in the fiducial volume (in a target module and no more than 0.24 m in the horizontal direction from the center of a module).

These cuts removed events triggered by high-momentum muons that interacted in the material surrounding the target and its support system sending secondary particles into the target area.

After these cuts were applied, events with a reconstructed vertex that was consistent with a neutrino interaction were selected in a visual scan, leaving 285 events in the data compared to 186 expected from a Monte Carlo simulation. The excess in the data was caused by the interaction of low-energy neutrons or photons in the most downstream target module. These events were removed by requiring a signal of at least 2 GeV in the lead glass calorimeter if the interaction vertex was in the most downstream target module. This cut reduced the number of events to 100 in the data and 95 in the Monte Carlo.

The remaining ν-N scattering background events were removed if there were any tracks in the event not associated with an electron or if secondary particles from the nuclear breakup were identified upstream of the interaction vertex. Events were also rejected if any reconstructed track was identified in the muon ID system, if the ratio of the measured momentum of a track to the signal in the electromagnetic calorimeter was less than 0.5, if a track crossed more than two radiation lengths of target material without initiating a shower, or if the track left a sequence of large energy deposits in neighboring layers of the scintillating fiber tracker. Once these tests were applied 13 events remained.

As a final test, events were selected if there was an identified electron at an angle of less than 30 mrad with respect to the neutrino direction and if there were no reconstructed large-angle tracks with angles in excess of 500 mrad. This left one event, shown in figure 1, an interaction in the most downstream target module.

IV. DATA ANALYSIS

The expected number of events from Standard Model processes was determined by a GEANT Monte Carlo simulation of the apparatus. The same program was used to find the selection efficiency for magnetic moment interactions. The accuracy of the simulation was tested by comparing data and simulation for two different sets of well-understood and easily identifiable events. The first set of control events consisted 200 ν_μ charged-current interactions containing an identified muon.

The second set consisted of 150 straight-through muons collected for calibration and alignment that scattered off an electron in the target region which in turn produced an electromagnetic shower. The electron energy spectrum of these "knock-on" electrons drops as $1/T_e^2$, while for magnetic-moment interactions it depends on $1/T_e$ (see equation 1.1). Though not identical, the similarity of the spectrum allows this control set to be used to quantify the effect of each selection cut on electromagnetic showers.

As a test of our simulation each cut applied to the data was also applied to both sets of control events. No significant difference between data and Monte Carlo was found with each cut removing the same fraction of events from both data and Monte Carlo for both control sets within statistical uncertainty.

The Monte Carlo was also used to estimate the overall detection efficiency for electron events. As the event trigger required at least one hit in the most downstream of the trigger planes (T3), the shower from electrons produced in the neutrino interaction had to pass through two radiation lengths for each emulsion module. The acceptance was further limited by a 6 mm thick lead shield that was placed between the target region and T3. The overall trigger efficiency for events where neutrinos interact electromagnetically with electrons was $(26.8 \pm 1.4)\%$, ranging from 10% for interactions in the upstream lead wall to 50% for interactions in the most downstream module and, after the neutrino interaction selection cuts $(15.2 \pm 0.8)\%$ of this type of events remained. By further requiring an identification of an electromagnetic shower in the event, the overall selection efficiency was reduced to $(9.0 \pm 0.6)\%$.

V. FLUX CALCULATION

The fixed target D-meson production cross sections using a proton beam are $\sigma_p(D^\pm) = (11.3\pm2.2)\mu b$/nucleon, $\sigma_p(D^0) = (28.0\pm2.5)\mu b$/nucleon, and $\sigma_p(D_s) = (5.2\pm0.8)\mu b$/nucleon [18]. All cross sections were found to increase linearly with the atomic mass. For comparison, the previous CERN experiment used a value of $\sigma_p(D_s) = 2.6\mu b$/nucleon at a beam energy of 400 GeV [5], for which this calculation yields a value of $2.4\mu b$/nucleon.

The differential cross section for D production was modeled by

$$\frac{d^2\sigma}{dp_t^2 dx_F} \propto (1 - |x_F|)^n \exp(-bp_t^2) \tag{5.1}$$

with values of $n = (7.4 \pm 0.6)$ and $b = (0.94 \pm 0.06)$ GeV^{-2} [18].

The branching ratio for the decay $D_s \to \tau\overline{\nu}_\tau$ is $(6.3 \pm 0.5)\%$, based on recent measurements of the decay [19]. The resulting ν_τ flux is $(2.1 \pm 0.3) \times 10^{-5}\nu_\tau m^{-2}\mathrm{POT}^{-1}$.

VI. RESULTS AND DISCUSSION

The single event surviving all the cuts occurred in the most downstream module and produced a narrow shower of particles with a reconstructed track at its center that had an angle of (10 ± 5) mrad with respect to the neutrino direction. The total recorded signal in the calorimeter was 20.0 GeV, of which 16.8 GeV were associated with the central part of the electromagnetic shower. For this energy, the electron angle should be less than 7 mrad according to Eq. (1.2). The selected event could be a quasi-elastic ν_e-N interaction with a relatively low-energy neutrino.

The expected background rate due to neutrino-nucleon scattering was 2.3 events and other processes, such as neutral current neutrino-electron scattering, are expected to contribute less than 0.05 events. Since we observed one event when the expected background rate was 2.3 events, we conclude that we did not observe any signal events, and therefore the measured magnetic moment is zero. A statistical analysis based on the Feldman-Cousins method [21] yields a 90% upper confidence limit of 2.3 events in the signal.

To convert this limit in the number of signal events to a limit on the tau-neutrino magnetic moment, Eq. 1.1 is integrated numerically, taking into account the calculated ν_τ energy spectrum. This yields

$$\sigma^{\mu}_{tot} = \frac{\mu_\nu^2}{\mu_B^2} \times 1.8 \times 10^{-28} m^2. \tag{6.1}$$

In the experiment a total of 3.56×10^{17} protons on target were recorded, and the average target mass during the run was 554 kg, corresponding to 1.7×10^{29} target electrons, hence the number of expected events for a given magnetic moment, given by the product of the flux, cross section, and number of scattering centers, is:

$$n_{\text{events}} = \frac{\mu_\nu^2}{\mu_B^2} \times 1.5 \times 10^{13}. \tag{6.2}$$

This gives an upper limit for the magnetic moment of $\mu_\nu < 3.9 \times 10^{-7} \mu_B$. This should be compared to the experimental sensitivity of $4.9 \times 10^{-7} \mu_B$, which is the limit that would be obtained had we observed as many events as predicted for the background.

This analysis is flavor-blind and the limit applies in principal to the sum over all neutrino flavors. However, more stringent limits have been determined by other experiments for ν_e and ν_μ. Assuming a magnetic moment at the current limit, their contribution would be less than 10^{-4} events. The limit is therefore interpreted as a new upper limit on ν_τ.

While systematic uncertainties were not included in this analysis as they are not part of the Feldman-Cousins method, they would only change the result slightly, since the uncertainty due Poisson statistics completely dominates the estimate of the limit. Contributions to the systematic uncertainty come from the neutrino flux calculation (15%), the total proton flux (15%), and the number of generated Monte Carlo events (5%). In addition to the statistical analysis based on the Feldman-Cousins method, a Bayesian analysis was performed including all these systematic uncertainties [22] using a flat prior distribution in the magnetic moment. This yields a 90% confidence limit of $\mu_{\nu_\tau} < 3.5 \times 10^{-7} \mu_B$. We include this result for comparison. However, only the upper limit derived with the Feldman-Cousins method should be quoted.

VII. CONCLUSIONS

The new upper limit for the tau-neutrino magnetic moment of $3.9 \times 10^{-7} \mu_B$ is an improvement over the previous limit [5]. Moreover, this is the first experiment to directly observe ν_τ charged-current interactions and therefore be certain to have a ν_τ component in the neutrino beam.

The new limit is still three orders of magnitude above the limits for ν_e and ν_μ, and it dominates when extracting limits for the mass eigenstates from the current limits for the flavor eigenstates. Improving the limit on μ_{ν_τ} would require a ν_τ beam that is comparable in total flux to previous ν_e and ν_μ beams.

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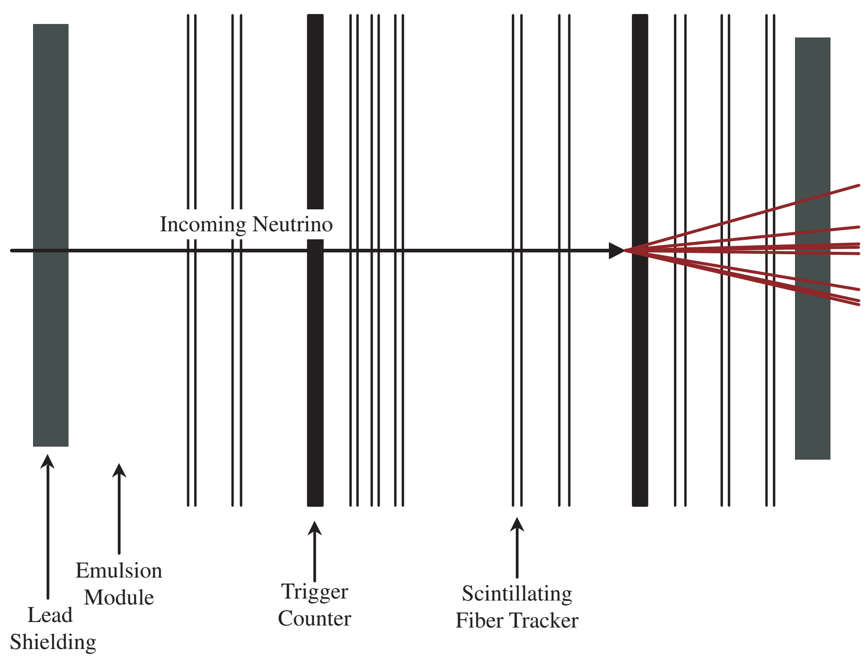

FIG. 1. Target region view of the selected magnetic moment candidate event. The neutrino is incident from the left.